SPECTROSCOPY OF NEUTRON-RICH C, O, N AND F ISOTOPES WITH THE AGATA+PARIS+VAMOS SETUP AT GANIL*

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(Received January 7, 2019)

Recent *ab initio* calculations pointed out the importance of the three-body terms of the nuclear interaction, in the description of the structure of n-rich systems. The state lifetimes in light n-rich carbon and oxygen nuclei have been predicted to be sensitive to the three-body terms and, in

* Presented at the Zakopane Conference on Nuclear Physics "Extremes of the Nuclear Landscape", Zakopane, Poland, August 26–September 2, 2018.

this context, an experiment, aiming at the measurement of these lifetimes, was performed in GANIL in July 2017 with the AGATA and PARIS arrays coupled to the VAMOS++ magnetic spectrometer. Details on the AGATA preliminary data analysis are presented.

DOI:10.5506/APhysPolB.50.625

1. Introduction

The investigation of excited states of n-rich light nuclei can provide relevant information on the nucleon–nucleon interaction, especially on the role played by the three-body terms of the nuclear force: recent *ab initio* calculations predicted a strong sensitivity of the electromagnetic transition probabilities of these excited states to the details of the nuclear force.

Among the most interesting cases there are ^{16}C and ^{20}O: theoretical calculations [1, 2] predict different electromagnetic transition probabilities for the second 2^+ states in these nuclei, depending on the presence of three-body terms (NNN) or considering two-body terms (NN) only.

Therefore, the main goal of the experiment described in the following is the measurement of the lifetimes of the second 2^+ state in ^{20}O and ^{16}C, populated through a deep inelastic reaction induced by an ^{18}O beam on a thick ^{181}Ta target. Here, we will concentrate mainly on the preliminary data analysis of the γ radiation, detected with the AGATA array.

2. Experimental setup and reaction

The experiment was performed at the Grand Accélérateur National d'Ions Lourds (GANIL) in Caen, France, in the period from the 11^{th} to the 23^{rd} of July 2017. The experimental setup was composed of 31 HPGe detectors of the Advanced Gamma Tracking Array (AGATA) [3], coupled to a scintillator array (at 90°), made of two large volume (8.89 cm × 20.32 cm) $LaBr_3$ detectors plus two complete clusters of the Photon Array for Studies with Radioactive Ion and Stable Beams (PARIS) [4] and to the VAriable MOde high acceptance Spectrometer (VAMOS++) [5], placed at 45° with respect to the beam direction and aligned with the centre of AGATA.

The nuclei of interest were populated via a deep inelastic reaction induced by an ^{18}O beam at 126 MeV (7.0 MeV/u) on a ^{181}Ta target, 4 μm thick 6 mg/cm^2). In the reaction, a wide range of isotopes was produced, as summarised in the map shown in the inset of Fig. 1. The reaction products were identified in the VAMOS++ spectrometer, while the emitted gamma rays were detected in the AGATA and PARIS arrays. As an example, we report in Fig. 1 the AGATA Doppler corrected gamma-ray energy spectrum obtained in coincidence with the ^{19}O ions detected in VAMOS++.

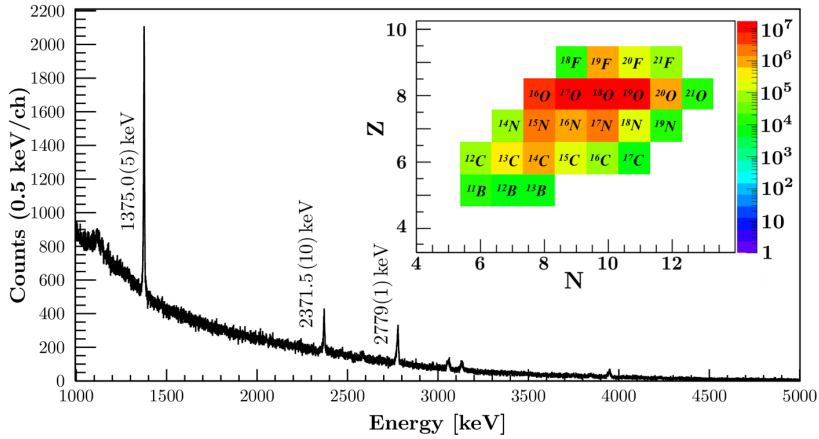

Fig. 1. Doppler corrected AGATA γ-ray energy spectrum measured in coincidence with ^{19}O ions. The histogram in the inset (number of protons Z *vs.* number of neutrons N) reports the statistics of the ions produced in the reaction process and detected in VAMOS++ (considering the most intense charge state only), and for which γ rays have been measured in AGATA.

3. Data analysis

The experiment required an accurate preliminary analysis: we report here some details on the AGATA data treatment, while further information on the PARIS and VAMOS++ data analysis is reported in [6]. A full replay of the entire data set has been performed, introducing precise time and energy calibrations for the AGATA detectors, following the procedure described in [7].

Concerning the time alignment of the AGATA detectors, it was found that most of the crystals were already aligned, apart from the ones using the new GGP (Generic Gigabit Processor) [8] electronics, as can be seen in Fig. 2 (a). A procedure aiming at aligning the crystals was implemented: appropriate time parameters were inserted in the replay configuration file, obtaining the result shown in Fig. 2 (b). The precise time correction permitted to put stringent gates on the prompt coincidence between VAMOS++ and AGATA, obtaining an improvement of the peak-to-background ratio of a factor > 2, with a loss in the counts in the photopeak less than 4%.

After the time alignment, a very accurate energy calibration had to be applied. Two calibration sources were used to perform the energy calibration of the core signal of the AGATA detectors: ^{152}Eu, for γ-ray lines below 1.5 MeV and AmBe:Fe, for γ lines above 5 MeV. In the intermediate energy region (2–3 MeV), we exploited the radiation coming from ^{208}Pb and ^{24}Mg, present in the surrounding materials, whose peaks were visible in the ^{152}Eu

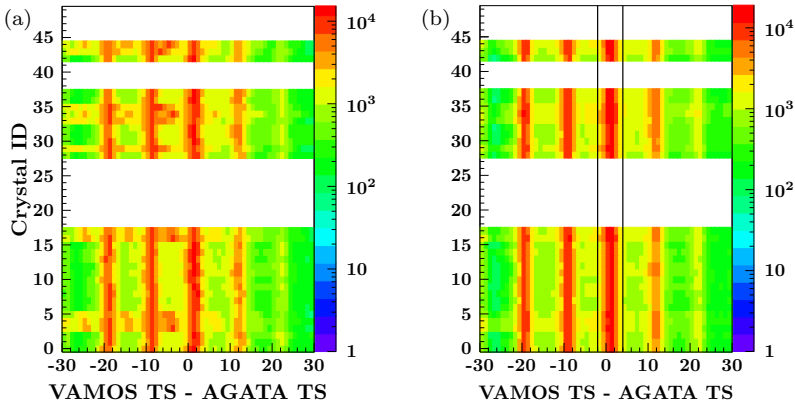

Fig. 2. 2D timing histograms before (a) and after (b) the time alignment procedure. On the y axis, there is the AGATA crystal identification number (Crystal ID) and on the x axis, the difference between the VAMOS++ and the AGATA timestamps (TS). The gaps are due to the missing detectors in the AGATA flanges. The black lines in (b) refer to the prompt coincidence gate used in the analysis.

spectrum. The peaks were fitted with a Gaussian function and a linear background and, after that, a linear regression has been performed, in order to find the energy *vs.* channel correspondence.

It was noticed that two of the AGATA crystals (number 14A and 11C) had degraded core signal: to recover them, an automatic procedure has been applied for the calibration of the 36 segments composing the detectors (see Fig. 3 (a) for a comparison of the core and segments energy spectra). Figures 3 (b) and 3 (c) show a portion of the AGATA energy spectrum (for the ^{152}Eu source), for each crystal, before, *i.e.* when using a raw calibration, and after performing the fine calibration, pointing out the large improvement in the energy resolution in all the regions of the spectrum, as reported in Table I.

TABLE I

Comparison between the energy resolution of the AGATA crystals, for different transitions of ^{152}Eu, before and after the fine energy calibration.

Energy [keV]	Near-line resolution [%]	New resolution [%]
121.8	2.96	1.73
1112.1	0.30	0.26
2754	0.22	0.16

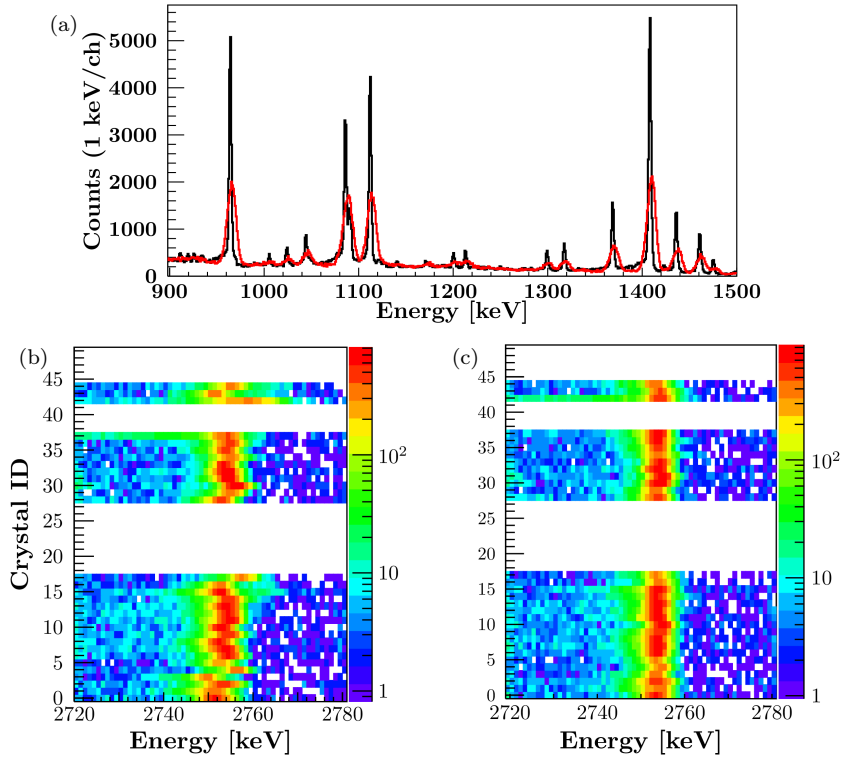

Fig. 3. (Colour on-line) (a) Comparison between the degraded core (grey/red) and the segments (black) energy spectrum of the crystal 14A. AGATA crystal identification number (Crystal ID) *vs.* γ-ray energy in keV 2D histograms, showing the ^{24}Mg peak at 2754.007(11) keV present in the ^{152}Eu source spectrum, before (b) and after (c) the energy calibration procedure.

The precise preparation of the AGATA data described above was necessary for the extraction of the states lifetimes through the analysis of the lineshape of the γ transitions in the nuclei of interest. As an example, we report here the test case of ^{18}O in which we measured the barycentre of the peaks of the γ rays at nominal energies 1938.2(2) keV and 1981.93(9) keV, de-exciting states with lifetimes $\tau = 26.5(29)$ fs and $\tau = 2.80(7)$ ps, respectively, as a function of the angle between the ion detected in VAMOS++ and the γ rays in AGATA. As can be seen in Fig. 4, a clear sensitivity to the lifetime is shown, which is manifested by the shift of the peak, when dealing with short lifetimes (few tens-hundreds of fs). Such a sensitivity can be exploited to extract lifetimes in this range, comparing experimental and simulated spectra at different angles, following the procedure described in [6].

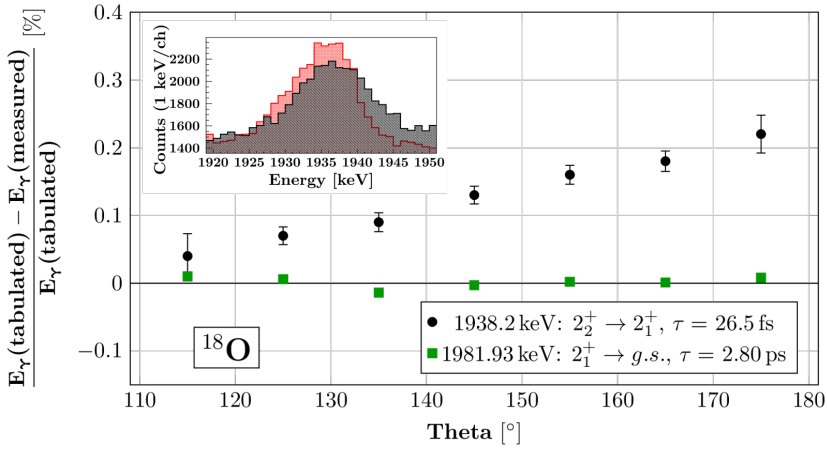

Fig. 4. (Colour on-line) ^{18}O analysis of the barycentre energy shift, as a function of the detection angle, for the 1938.2 keV and 1981.9 keV lines, depopulating states with 26.5 fs and 2.80 ps lifetimes, respectively. The error bars of the green dots series are smaller than the symbols. In the inset: comparison of the ^{18}O peak at 1938.2(2) keV at 135° (black) and 155° (grey/red).

4. Conclusions

Very precise time and energy calibrations have been applied to the AGATA data obtained in the deep inelastic reaction ^{18}O(126 MeV)+^{181}Ta. The aim is to extract the lifetimes of excited states in neutron-rich O and C ions, which are expected to be sensitive to the three-body terms of the nuclear interaction. Using ^{18}O as a test case, a preliminary analysis shows a clear sensitivity of the shift of the γ peaks in energy, as a function of the detection angle, to short lifetimes, in the range of interest of few hundreds of femtoseconds. Such a sensitivity will be exploited to extract the state lifetimes, using a sophisticated simulation of the reaction process, currently under development.

This work was supported by the National Science Centre, Poland (NCN) under contracts No. 2013/08/M/ST2/00257, 2014/14/M/ST2/00738 and 2016/22/M/ST2/00269.

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